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LUNAR PREFORM MANUFACTURING

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I. ABSTRACT

A design for a machine to produce hollow, continuous fiber reinforced composite rods of lunar glass and a liquid crystalline matrix using the pultrusion process will be presented. The glass fiber will be produced from the lunar surface, with the machine and matrix being transported to the moon. The process is adaptable to the low gravity and near-vacuum environment of the moon through the use of a thermoplastic matrix in fiber form as it enters the pultrusion process.

With a power consumption of 5kW, the proposed machine will run continuously, unmanned in fourteen day cycles, matching the length of moon days. A number of dies could be included that would allow the machine to produce rods of varying diameter, I-beams, angles, and other structural members. These members could then be used for construction on the lunar surface or transported for use in orbit.

The benefits of this proposal are in the savings in weight of the cargo each lunar mission would carry. The supply of glass on the moon is effectively endless, so enough rods would have to be produced to justify its transportation, operation, and capital cost. This should not be difficult as weight on lunar mission is at a premium.

II. INTRODUCTION

A. Purpose

The purpose of this project was to design a process to form long lengths of hollow glass filament reinforced composite rods on the moon. It is believed that glass can be produced from compounds present in lunar regolith. By producing the glass in a vacuum, it is possible to achieve high tensile strength and a better fatigue life due to a lack of flaws in the fiber and to less crystallization of fibers after creation.

It is estimated that producing rods on the moon with the available lunar glass would result in a significant monetary savings when compared to the cost of transporting pre-manufactured rods from Earth to the moon.

B. Possible Uses For Rod

These rods would be used as reinforcing beams in a number of lunar structures. Some of the suggested uses are structural members for platforms, large space antennas, long tethers, and solar reflectors. Another possibility for the use of the rods is to transport them from the lunar surface to future space stations to be used in construction.

C. Constraints

The project was limited by the following set of constraints. All processing involved in the production of the composite rods will be done on the surface of the moon. It was assumed that the glass fiber needed for rod production would be readily available and packaged in a form suitable for use in the composite manufacturing process. All other processing materials would have to be transported to the moon. Because of the high cost of space transportation, it is necessary that the weight be kept to a minimum. Five kilowatts of power will be available for the entire process.

It is required that the process be flexible enough to produce rods that vary in inner diameter from 1 cm to 10 cm. The varying size rods would be used for different applications based on strength requirements.

D. Lunar Environment

The hostile conditions present in the lunar environment require that special consideration be taken in material selection. The temperature for the lunar surface ranges from -261 F at night to 234 F in the day. The lunar day is equivalent to 14 Earth days followed by an equal period of darkness. The gravity force on the moon is equal to one sixth that of Earth. Radiation in the forms of solar radiation, solar energetic particles, and galactic cosmic radiation poses a moderate to high danger and must be considered

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when using a polymeric substance. Dust protection is also required on the lunar surface.

Following these constraints and considerations, a pultrusion process was designed to produce a glass composite rod with a thermoplastic matrix on the lunar surface. The process components and materials selection are described in the following report.

III. PROCESS

A. Manufacturing Methods

Five different methods for manufacturing fiberglass composite rods were considered for use on the moon. Each method was judged primarily on its simplicity and on the rod properties that could be obtained. Because of the limiting factors of the lunar environment, machine simplicity took precedence over optimal rod properties.

1. Braiding

Braiding involves packages of yarn traversing on a circular rail forming a continuous tube. The tube is braided onto a mandrel which gives shape and support to the structure as the matrix is applied and curing takes place. The tube would be pulled from the curing oven and cut to the desired length.

While braiding provides excellent tensile and compression properties, the complexity of the machine makes it a poor choice for use in a lunar environment. Because the packages of yarn have to be located on the travelers, package size is limited. This increases the amount of automation or labor required to change out empty packages.

Another disadvantage of braiding is the large number of moving parts required. The greater the number of moving parts, the less reliable the machine will be. Lubrication must be provided for the moving parts which presents a problem when working in the lunar environment. Lubrication tends to flash off in a vacuum. Therefore, it is best to use a process with few moving parts and minimize the need for lubrication.

2. Filament Winding

The next process considered was filament winding. Filament winding involves wrapping a continuous yarn over a rotating mandrel to form the rod. The yarn is wrapped in layers at varying angles to achieve the desired thickness and properties. The filament carriage traverses longitudinally to provide full coverage. Filament winding offers the advantages of few moving parts and the ability to alter rod properties simply by changing the angle at which the yarn is wound.

The main disadvantage of filament winding is that it is a discontinuous process. The length of the mandrel limits the length of the rod produced. When the rod is complete, it must be removed and transported to a curing oven and a new mandrel put in its place. The yarns must then be tied in and the process restarted. This is a very labor intensive process which increases the cost of running filament winding.

3. Nonwovens and Laminates

Nonwovens and laminates were considered next. These two forms of composite preforms can be discussed together because of the similarity of their form. Nonwovens involve producing a mat of randomly arranged fibers and rolling and bonding it to form a tube. Likewise, laminates involve producing a woven mat which is rolled and bonded at the seam.

Laminates were almost immediately ruled out because of the complexity of the weaving process. While nonwoven formation is a simpler process, the problem of forming the preform into a rod still exists. The mechanical properties of the rod will be greatly reduced at the seam of the rod. The reduction in strength in laminates and nonwovens suggests that a continuous tube would be a better choice of preform.

4. Pultrusion

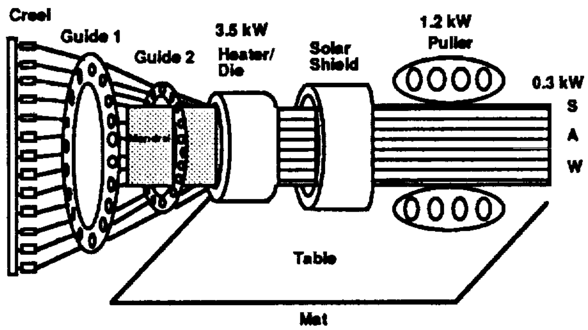
Finally, pultrusion was considered for forming fiberglass composite rods on the moon. Pultrusion involves pulling parallel yarns through a heated die where the fibers and melted matrix form a rod. The rod is then cooled and cut to the desired length. The only moving parts involved in this process are the puller rollers, thereby minimizing the need for lubrication and increasing the degree of reliability.

Though the strength properties are sacrificed somewhat by having the yarns lie parallel, the simplicity of the process outweighs the reduction in strength. Pultrusion also offers the advantage of being able to make many different shaped structures simply by changing the die. The simplicity and flexibility of pultrusion make it well suited for use in the lunar environment.

Figure III.A.4.1

LUNAR PULTRUSION MACHINE

(Conceptualization)



IV. PULTRUSION MACHINE

A. Machine Components

1. Creel

Package Size

Package size was determined by the amount of fiber, both reinforcement and matrix, necessary to allow the machine to run 336 hours (14 days) without interuption for package replacement. Based on the calculated rate of the machine, each package of glass tow (40 fibers/tow) and Vectran would have to contain:

L = rate X time = .001875 m/s X 3600 s/hr X 336
= 2268m

Based on 50 packages of glass tow and 50 packages of Vectran, for a rod of 60% fiber volume fraction, an inner diameter of 10 cm and an outer diameter of 12 cm, each package would have to contain:

Composite Area = $p(r_O 2\text{-}r_i 2)$ = 34.56 cm^3
r_O = outer radius
r_i = inner radius

Volume of Composite = Area X Length
= 7,837,645.35 cm^3

Volume of Glass = 0.6 X Composite Volume
= 4,702,587.21 cm^3

Volume of Matrix = 0.4 X Composite Volume
= 3,135,058.14 cm^3

Mass of Glass = Density X Volume = 11,756.5 kg

Mass of Matrix = Density X Volume = 4,389.1 kg

Mass of Package(Glass) = Total Mass/50 = 235.1 kg

Mass of Package(Matrix) = Total Mass/50 = 87.8 kg

From this information, the package size is easy to calculate, assuming a cylindrical package with length of 38.1 cm, inner radius of 2.5 cm, and a packing factor of 0.9:

Volume of Package(Glass)
= 235.1/(density X packing factor)
= 104,489 cm^3

$p(r_O^2\text{-}r_i^2)$ X length = 104,489 cm^3

r_O = 29.65 cm

Volume of Package(Matrix)
= 87.8/(density X packing factor)
= 69,682.5 cm^3

$p(r_O^2\text{-}r_i^2)$ X length = 69,682.5 cm^3

r_O = 24.26 cm

In addition, the denier of the tow and the matrix would be:

Denier of Tow = ((235.1X1000)/2268) X 9000
= 932,936.5

Denier of Matrix = ((87.8X1000)/2268) X 9000
= 348,412.7

These linear densities are extremely high, and would have to be achieved by twisting of conventional denier tows and yarn, or the number of packages could be increased.

Creel Specifications

It was determined that a V-creel would be purchased for this design. This creel would have posts of length 40.6 cm and diameter 1.25 cm, prefitted with a Black Bros. cone locking device. Its capacity would be 100 cylindrical packages of maximum outer diameter = 30 cm and length = 38.1 cm. In addition it would have to be made of a lightweight, strong material (Aluminum 6061-T6) and all packages would have to be accessible to the average person without strain. Based on all of these constraints, the two halves of the V-creel will be approximately 10 m in length and 2 m high.

2. Guides

Two guides are used to guide the 100 strings of glass fiber and matrix from the creel to the heater/die. Guide #1 has a 92 cm outer diameter and a 84 cm inner diameter with 50-two cm diameter holes for the glass rovings and matrix fibers. Guide #2 has a 30 cm outer diameter and a 22 inner diameter with 25-two cm diameter holes for threading four strands- 2 of glass fiber and 2 of matrix. Both guides were cast out of 6061-T6 Aluminum with a uniform width of 1.5 cm. Each of the guides are welded to a stand which enables them to be moved as needed for the various sizes of rods being manufactured.

3. Mandrel

The mandrel is a 3.5 m hollow tube which will impart both shape and support to the pultruded rod. The mandrel will begin between the first and second guides and end before the puller. The mandrel will be made of Aluminum 6061-T6 and coated to provide insulation. The insulating layer will prevent the mandrel from conducting heat away from the heated die thereby increasing the power required to maintain the necessary die temperature.

The mandrel will have a hollow construction to minimize the weight. The mandrel will be threaded inside one end to allow it to be joined to the mandrel stand.

The mandrel stand will be constructed of Aluminum 6061-T6. It is composed of an L-shaped shaft with a threaded extension. The stand will be bolted to the mat on which the machine rests.

It will be necessary to have a set of mandrels of varying diameters in order to produce rods between 1 and 10 cm inner diameter. For mandrels of less than 6 cm inner diameter, a reducer will be required to join the mandrel to the stand.

4. Heat Die

The central process feature of pultrusion is the control of the resin/catalyst chemical reaction under the influence of heat. This has to be done in such a way that the resin gelation point and the peak exotherm point both occur inside the die while the curing mass is continuously moving. Failure to do so results in incomplete cure, exotherm occuring outside the confines of the die, and quality deterioration in the form of cracks in the profile. Since Vectra is a liquid crystal polymer, the problems associated with curing are eliminated since there is no curing involved. The reaction is instantaneous. The melting process is the rate determining step for the process.

Material Selection

The design of the electric heat die involves the following four things: the electrical resistor, the heat conducting die, the insulator, and the coating. While considering these different aspects, it should be kept in mind that only five kilowatts is allocated for the whole machine. Although the heat die is what usually consumes the most power, minimum energy use should always be kept in mind.

The electric resistor is what heats the die. It should be a material that is resistive enough to produce maximum heat, and yet conductive enough to allow current to pass through it. The most common heater resistors are Nichrome, Incoloy, Copper, and steel. The material chosen for this particular heat die is Nichrome (66% Ni + Cr & Fe) which is used by Creative Pultrusions Inc.. Nichrome has a resistivity of 1000 E-9 W.m at room temperature. Since the Vectra processing/melting temperature is 300 C, and thus the temperature of the die, the the resistivity at 300 C is calculated as follows:

resistivity =
(resistivity at room temperature)[1+(coefficient of thermal resistivity)(temperature - room temperature)]

resistivity = (1000 E-9)[1 + .0004(300-20)]
= 1.112 E-6 W.m

The material of the die has to be a very good heat conductor to transfer the heat efficiently to the composite. It has to have low specific heat so as to limit the energy needed to heat it up. Finally it is preferable to have low density for transportation cost reasons. Commercial heat dies for pultrusion machines are made of stainless steel to withstand the expansion forces generated during the resin polymerization. But since: 1) Vectra has a very low coefficient of expansion (transverse = 65 E-6 cm/cm/C, linear = 5 E-6 cm/cm/C), 2) it has the advantage af low melt viscosity due to the liquid crystalline behavior, 3) the die is surrounded by an insulator which adds support to the die, 4) the fact that the tube is being pulled at an extremely low velocity (.1125 m/min as opposed to commercial 1 m/min), the strength of the material is not such a big factor. The following materials were considered:

Table IV.A.4.1

Material (at 300 C)	K (W/m.K)	Cp (J/Kg.K)	r (Kg/m^3)
Al (pure)	232.2	1021.7	2702
Cu (pure)	380.9	414.3	8933
Gold	300.4	129.5	19300
Steel AISI 347	17.5	552.7	7978
Silver	413.8	248.6	10500

Looking at these values in the order of importance (high K, low Cp, then low r), silver is a good choice (melting point = 1235 k).

As for the insulator, looking at materials which are neither bricks nor organically bonded, the choice was alumina-silica fibers (density = 128 Kg/m^3, K = .0561 (W/m.k). These fibers could be melted to form a solid tube surrounding the die or they could be in the form of a blanket. The glass fibers could be the ones obtained from the moon.

To conserve energy and trap the heat generated, the insulator is coated or plated with a material having high absorptivity (a) and low emissivity (e). The following materials were investigated:

Table IV.A.4.2

Material	a	e	a/e
Aluminum Foil	.15	.05	3.0
AluminumPolished	.09	.03	3.0
Plated Sulfide	.92	.10	9.2
Plated Chrome	.87	.09	9.7

The clear choice is plated black chrome which has the highest a/e ratio.

Power Analysis

To calculate the power necessary to process the glass/Vectra composite, a heat transfer problem was solved. Due to the complexity of this problem, several assumptions were made:

1) The mandrel is perfectly insulated. Thus the temperature across the composite tube is constant (i.e. processing temperature 300 C).

2) The problem is considered to be a steady state problem (as opposed to transient). This eliminates the calculation of DU/Dt.

3) The temperature is considered to be constant along the heated die. The temperature only changes radially.

4) When considering the energy gained due to the solar radiation, only half of the surface area is considered to be exposed to the sun. The radiation reflected & emitted from the lunar surface and the machine to the second half of the die is ignored.

5) The temperature of the machine is assumed to be the same as the temperature of the lunar surface.

6) The energy associated with the heat of fusion is negligible. Thus (m/DT) h_{fg} = 0.

7) The thickness of the coating is very thin. So the conductivity of the plated black chrome is ignored.

8) The power consumed in these calculations, is the one associated after the die has reached 300 C. The power needed at the beginning to get the die to 300 C is not calculated since in that case the motor is not running and thus the die can use more than it's allowable share (up to five kilowatts). So determining the start up power would be useless, because it is not going to be the one dictating the consumption.

The amount of energy needed to melt the Vectra is $Q_{generated}$ (= the power supplied to the heat die = R I^2 = (resistivity) (Length/Area) I^2).

$Q_{generated} = Q_{loss} + (m/Dt)\ DT\ C_p$

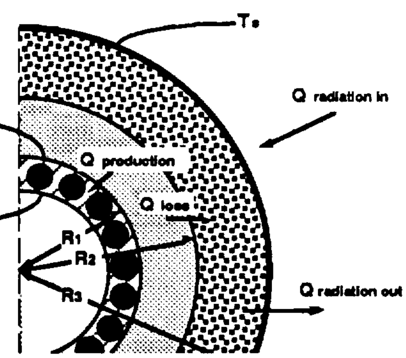


Figure IV.A .4.1

Q_{loss} = heat lost by conduction $= DT/R_{tot}$

$$R_{tot} = (573 - T_s)/\{[(\ln d_2/d_1)/2pKL] + [(\ln d_3/d_2)/2pKL]\}$$

where : Ts = surface temperature of the insulator
d = diameter
K = conductivity
L = length of the die

To calculate Q_{loss}, it can be seen that there are two unknowns (T_s & L). Ts can be calculated by taking an energy balance across the insulator. Heat going into the insulator (Q_{loss}) = heat leaving the insulator by radiation ($Q_{net\ radiation\ out}$).

$$Q_{net\ radiation\ out} = Q_{radiation\ out} - Q_{radiation\ in}$$

$$Q_{radiation\ out} = [e\ s\ (A_s/2)\ (T_s^4 - T_{space}^4)] + [e\ s\ (A_s/2)\ (T_s^4 - T_{machine}^4)]$$

$$Q_{radiation\ in} = 1400\ (A_s/2)\ a$$

where : s = Stefan-Boltzman Constant
= 5.67 E-8 W/m^2 K^4
A_s = surface area
T =temperature,
(T_{space} = 0 k & $T_{machine}$ = 385 k)
1400 = solar radiation (W/m2)

Equating $Q_{loss} = Q_{net\ radiation\ out}$, T_s is solved. This is done using trial and error since there is a T_s^4 and T term in the same equation. It should be noted that in these calculations the length is still unknown (i.e. L & A_s are unknown). To get around it different lengths are plugged in. The result is a power consumption vs length curve. This is done for different inside diameter tubes having 1 cm thickness. Qloss is calculated using Ts.

The second term in the $Q_{generated}$ formula is the power consumed by the production rate ($Q_{production}$) = (m/Dt) DT C_p.

$$(m/Dt)\ DT\ C_p = [(m\ Cp)_{vectra} + (m\ Cp)_{glass})]\ (DT/Dt)$$

Where: m = mass of composite tube in the die (corresponding to the length). This is done by considering Vectra to be 40% and glass 60% by volume.

DT = 573 - $T_{desired}$ ($T_{desired}$ = 385 k)
Dt = time it takes to reach $T_{desired}$ for a given die length

It can be seen that in this case Dt is unknown. To solve this problem, different Dt's are chosen.

So by varying L and Dt, $Q_{generated}$ is solved. This is done for different diameters, but since 10 cm inside diameter is the most energy consuming one, the power corresponding to that size is the one chosen (Appendix C) . It can be seen that as the length of the die increases, the power consumption increases. Also as the Dt decreases the power increases. That is as the velocity increases, the power consumption increases . Having three variables, power , time, and length of die , the die can be designed to fit the specific needs of production rate and power consumption. For the present case of a composite tube with inside diameter of 10 cm and 1 cm thickness, a die length of 75 cm with velocity .001875 m/s consumes 3386.093 Watts.

Die Description

The heat die is made up of two parts, a top part and a bottom part (Appendix C). When starting the process, the top part is taken off, the Vectra/glass fibers put in and then the top part put back on. This two part assembly makes the threading process much simpler. Likewise the insulator surrounding the die is also made up of two parts (top and bottom part). The dies for the different diameter sizes are made the same way. They all have two centimeter thickness dies, with three and a half centimeter thickness insulators.

5. Solar Shield

Once the composite tube leaves the heat die, it enters a very thin cylindrical tube. The purpose of this is to cool the material and solidify it before it reaches the puller. Without the solar shield, the puller would have to be spaced a considerable distance from the heat die. This would lead into a larger power consumption since more material would have to be pulled.

Material Selection

The material chosen should have a very high emissivity and very low absorptivity. This is due to the fact that the shield needs to radiate out as much of the heat from the composite tube as possible. The following materials were considered:

Table IV.A.4.3

Materials	a	e	a/e
Aluminum quartz overcoat	.11	.37	.30
Aluminum anodized	.14	.84	.17
White acrylic paint	.26	.90	.29
White zinc oxide paint	.16	.93	.17

Looking at these materials, white zinc oxide paint, and anodized aluminum have the lowest a/e ratio. Considering that oxides do not last in space due to degassing, the anodized aluminum is chosen.

Cooling Analysis

The main purpose of this analysis is to determine the length of shield needed to cool down the Vectra/glass tube from 573 k (processing temperature) to 385 k (lunar surface temperature). This is done knowing the velocity of the composite from the previous calculations. The thickness of the solar shield is very small, so no conduction is taken into consideration. The only form of heat exchange is by radiation. To simplify the calculations, some assumptions are made:

1) Only half of the surface area is considered to emit or absorb radiation. This is done because of the difficulty in calculating the view factor of a semi-cylinder on a flat surface (the surface is not even flat). In addition this surface factor changes with time as the sun's incident rays change their angle as the days pass by.

2) The formula used for the net radiation exchange between two concentric circles is for the case of infinitely long cylinders. So the shield and the composite tube are considered to be very long.

The main heat transfer analysis is as follows: The heat associated with the production rate is equal to the net radiation heat exchange between the composite and the solar shield.

$$Q_{production} = m\,C_p\,(DT/Dt) = Q_{net\ radiation\ exchange}$$

$$Q_{net\ radiation\ exchange} = \frac{s\,A_t(T_r^4 - T_s^4)}{[(1/e_1)+((1-e_2)(d_1/d_2)/e2)]}$$

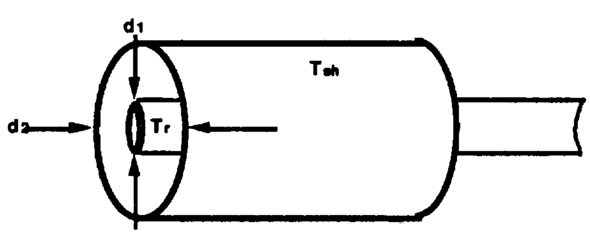


Figure IV . A . 4. 3

where: A_t = surface area of the composite tube
e_1 = emissivity of composite tube
e_2 = emissivity of solar shield
d_1 = outside diameter of composite tube
d_2 = diameter of solar shield
T_r = temperature of the rod = 573 k

This equation has three uknowns: length, diameter, and T_s. The length problem is solved by trial and error. Different values are plugged in and when $Q_{production} = Q_{net\ radiation\ exchange}$ that is the solution. As for the diameter, the bigger the value the more surface area available for the radiation exchange. But since the tube is at a limited distance from the machine, the diameter is chosen as 80 cm. Taking a control volume at the surface of the shield, the radiation flowing out of the Vectra/glass tube and into the shield is the same as the net radiation leaving the surface of the shield. So T_s is solved for by equating:

Q net radiation exchange between the tube and solar shield = Q net radiation leaving the shield.

$$Q_{net\ radiation\ leaving} = Q_{radiation\ out} - Q_{radiation\ in} = (e_2\,A_{sh}\,T_s^4) - 1400\,a\,(A_{sh}/2)$$

where: A_{sh} = surface area of the solar shield
a = absorptivity of the solar shield

Once T_s is solved for, $Q_{net\ radiation\ exchange}$ is determined.

$$Q_{net\ radiation\ exchange} = m\,C_p\,(DT/Dt) = A\,v\,r\,DT\,C_p = [(.6\,A\,r\,C_p)_{glass} + (.4\,A\,r\,C_p)_{Vectra}]\,v\,DT$$

where: A = cross sectional area of the tube
v = velocity (previously determined)
r = density

So for a certain velocity both $Q_{production}$ and $Q_{net\ radiation\ exchange}$ are determined. Once these values match, that is the solution for the shield length. All this is dependant on the velocity determined from before. For the case of 10 cm inside diameter and 1 cm thickness composite tube travelling at .001875 m/s the length of the shield is calculated to be 2.25 m (Appendix C).

Solar Shield Description

The solar shield is a cylinder made up of two equal parts, a bottom and a top part. This is done so as to make it easier for the astronauts to get the fibers through at the start of the process.

6. Puller

The function of the pultrusion puller is to put a large enough load on the pultruded rod to cause friction between the belt and rod. A torque is applied to the belt in order to extract the rod from the heat die. The design constraints impose a number of difficulties in the design of the device. The power constraint of 5 kW only allows for 1.2 kW to be distributed to the puller motor. The moon's environment is that of a vacuum where the reduced ambient pressure and absence of oxygen cause problems in the lubrication system and bearings. Lastly, the moderate to high radiation danger and temperature requires special materials for the mechanism.

Motor

An analysis of the motor power consumption shows that 1.2 kW will suffice even with a conservative estimate. The pultrusion device is designed to produce rods at .001875 m/s. This means that the motor shaft must turn the 5 cm O.D. at 0.012 rad/s.

$$w = v/2Pr$$
$$= (0.001875\ m/s)/2P(0.025\ m)$$
$$=0.012\ rad/s$$

A calculation of torque and pulling force gives 100,000 Nm and 4000 kN respectively.

$$T = P/w$$
$$= (1200\ W)/(0.012\ rad/s)$$
$$= 100{,}000\ Nm$$

$$F = T/r$$
$$= (100{,}000\ Nm)/(0.025\ m)$$
$$= 4000\ kN$$

A simple calculation of the total mass of a pultruded rod as long as the machine gives a total rod mass and lunar weight of 71.2 kg and 116 kN.

$$m =P(r_o{}^2-r_i{}^2)L[.4r_{matrix}+.6r_{glass}]$$
$$=P(6^2-5^2)cm^2(1000\ cm)[.4(1.4g/cm^3) +.6(2.5g/cm^3)]$$
$$= 71.2\ kg$$

$$Wt =m(g/6)$$
$$= 71.2\ kg(9.8\ m/s^2)/6$$
$$= 116\ kN$$

From this data, a very conservative yet simple friction calculation proves that 1.2 kW will be more than enough power to a motor pulling 71.2 kg of glass. This can be estimated by assuming the rod's weight is the only applied normal force. Also, the major force restricting the motor is the frictional force of glass on aluminum. With a friction coefficient of 0.6 the friction force is less than 70 kN.

$$F_{friction} = \mu Wt$$
$$=0.6(116\ kN)$$
$$= 69.6\ kN$$

It seems highly improbable that all other minor forces added together could come close to 3930 kN. The minor, uncalculatable forces include the fiber tension at the creel and the restrictive forces at the guides and the vacuumated heat die.

Lubrication

The purpose of the lubrication system in a lunar environment as in any environment is multifunctional. All lubrication systems must reduce wear, support loads, and transfer heat. On the moon, the high temperatures require a lubricant to reduce friction over a wide temperature range. Lastly, a lubricant must prevent erratic performance, catastrophic failure, and cold welding.

The vacuum environment has a negative effect on conventional lubricants used on Earth. The reduced ambient pressure has a degassing effect on the lubricant while organic oils and greases tend to evaporate. Also, when lubrication is not present or has evaporated in an oxygen-depleted environment, mechanical components tend to cold weld.

The two major types of lubricants are those composed of organic materials or inorganic materials. Organic materials such as oils and greases are a poor choice for the lunar environment because they have a high evaporation rate at low vapor pressures. This forces a lunar designer to choose solid inorganic lubricants or metallic films. The second group of lubricants also have drawbacks. Solid lubricants have a finite endurance life and poor adherence to the lubricated component. Also, the friction coefficient is higher for solid lubricants than hydrodynamic lubricants.

Solid film lubricants can generally be defined as materials that provide lubrication to slow relatively moving surfaces under essentially dry conditions. The most common, and still the most widely used, of solid film lubricants, powdered graphite and molybdenum disulfide, have been known and used limitedly for more than 100 years. There are numerous advantages of solid film lubricants in a lunar environment such as the use over a wide temperature range, the resistance to nuclear and gamma radiation, no grit collection (lunar dust), and their excellent storage stability.

Two commonly used and logical lubricants for bearings and sliding surfaces in a lunar environment are Surf-Kote and Vac Kote. These molybdenum disulfide-based lubricants are often used in space applications because they exhibit low friction and high endurance under vacuum. Their properties are outlined in Table IV.A.6.1.

Table IV.A.6.1

Film Matl Desig-nation	Load	Speed	Temp. (F)	Avg Wear-Life	Vac'm Wt Loss
Surf-Kote M-2049	Med	Low to High	-65 to 500	246 min	0.233 mg/cm ^2
Vac Kote 21207	Low to High	Low to Med	-436 to 302	502 min	0.0775 mg/cm ^2

Vac Kote was chosen because of its capability to handle a wide range of loads, the longer wear life, and much lower vacuum weight loss. The composition of Vac Kote is primarily molybdenum disulfide serving as a solid film. The composition also includes grease formulations and organic compounds containing metallo-organic complexes and long chain hydrocarbon molecules. This lubricant has many other positive features for lunar applications such as 10,000 years of radiation exposure, the ability to handle a low vapor pressure, excellent outgassing properties, and an open configuration to save weight and maintain a high reliability.

Contact Materials

Studies of the tribological properties of molybdenum disulfide, when applied to ceramics and metals in a vacuum tend to favor a ceramic substrate. Friction coefficients tend to decrease with increasing elastic modulus of a contact material. This behavior is attributed to the contact area of the surfaces. Film endurance is strongly dependent on the substrate material. The highest endurance for molybdenum disulfide is the ceramic, silicon nitride and the worst durability for titanium alloys. Film durability is appears strongly related to adhesion, as evidenced by the presence of interfacial chemical bonds on steel and ceramic and lack there of on a titanium alloy surface. Test results and material properties are outlined in Table IV.A.6.2

Table IV.A.6.2

Matl	Hardns (GPa)	Elastic Mod (GPa)	Mean MoS_2 Film Endrnc	Rec'vd Surfce R'ghnes	Pol-ished Surface R'ghnes
Silicon Nitride	19.9	350	120 Krev	0.060 μ	0.060 μ
52100 Steel	7.3	200	15 Krev	0.109μ	0.055 μ
440C Steel	8.8	200	7 Krev	0.45 μ	0.046 μ
Ti Alloy (318)	3.2	106	400 rev	0.45μ	0.057 μ

Based on this data, the combination of molybdenum disulfide and silicon nitride gives a very favorable tribological performance under vacuum. Therefore, the material of choice for the pultrusion bearing applications will be the ceramic, silicon nitride.

General Discussion

The pultrusion puller has a belt that is spring loaded against the glass rod (See Appendix B). The puller must also have the capability to vary the gap from 1 cm to 10 cm. This requires a pulley system in the gearbox with varying radii (See Appendix B). Both the belt in the gearbox and the belt that pulls the glass rods require a radiation resistant material. A commonly used elastomer in space is a vitron fluor-elastomer. The operating range is between -50 and 450 °F enabling its use at high temperatures with many hydraulic fluids. This material is also highly resistant to weathering, has good mechanical properties, low permeability to gases, and fair radiation stability. As previously discussed, all other components such as the puller bracket (See Appendix B) will be of Aluminum 6061-T6.

7. Cutoff Saw

The cutoff saw is the last stage of the pultrusion process. The purpose is to periodically saw the rods into 10 m lengths. A timer/controller such as a mercury switch will be used to turn the saw on and off and to load the saw down to the rod. The timer setting can easily be determined by dividing the production rate by the desired rod length. The saw will be allowed a maximum 300 W.

8. Scray

The scray box will hold the completed three meter lengths of composite rods. The scray will be located immediately following the saw where the rods can drop into the box upon being cut.

The scray has the capacity to hold approximately 360 three meter rods of 12 cm outer diameter. It is estimated that 720 rods can be produced during one lunar day. Therefore it will be necessary to replace the full scray with an empty one midway through the operating cycle. The scray was designed with a folded lip on each side to allow it to be lifted and transported away from the production sight.

The scray will be constructed of Aluminum 6061-T6 to minimize the weight.

9. Rails

All the different components of the pultrusion machine are placed on a flat structure with rails (Appendix B). The purpose of the rails is to allow the different parts of the machine to be moved back or forth according to the need of the process. There are basically six parts to the pultrusion machine that are on these rails. The two guides, the heat die, the solar shield, the pulley system with the motor, and the saw at the end. The distance between these components is dependent on the diameter of the tube being produced. This mobility is especially helpful to reduce the friction by the guides. These guides can be put at such distances so to minimize the angle between the fibers (Vectra & glass) and the horizontal. The lower the angle, the less normal component of force, and thus the less friction ($F_{friction}$ =(m) (F_{normal})). The rail structure is made up of Aluminum 6061-T6. This is a common material used in the aerospace industry which has very good properties.

Table IV.A.9.1

Aluminum 6061-T6	
Ultimate Tensile Strength =	45 ksi
Yield =	40
Biernell Hardness =	77
Ultimate Shear Strength =	30 ksi
Modulus of elasticity =	10 E3 ksi

10. Tables

The three tables, 110 X 92 cm, were cast out of 6061-T6 Aluminum with a uniform width of one cm. Partial legs of 20 cm in length are part of the same cast. These partial legs have a threaded insert welded flush to the bottom of them. Detachable legs, 60 cm in length. have a nine cm threaded shank attached to the top end of each. These detachable legs are screwed into the partial legs with the shank used as a leveling device.

B. Dust Protection

Because of the rough terrain of the lunar surface, a 15 m x 15 m area should be leveled prior to the installation of the pultrusion unit. A mat constructed of a thin aluminum sheet with a neoprene foam on the underside will be laid out under the machine. The neoprene foam will aid in leveling out the surface on which the machine rests.

The mat would offer adequate protection from dust which would be stirred up by a person walking around the machine during threading and start up.

C. Start Up/ Shut Down

1. Method of Threading

A roving of glass fiber is clasped in the threading hook, shown in Appendix B, and strung through one hole of Guide #1, through one hole in Guide #2, through the runner and tied onto the cross bar at the end of the runner. A string of matrix is then strung in the same manner as the glass roving. A second sting of glass roving is clasped to the hook and threaded through a second hole in Guide #1 but through the same hole as the first set of glass/matrix in Guide #2 and attached to the runner in the same manner. This process is repeated for the remaining strings of roving with two strings of material per hole in Guide #1 and four strings of material per hole in Guide #2. Each string requires approximately two and one half minutes to thread for a total of five hours for the threading process.

When the threading process is completed, duct tape is wrapped around the left end of the runner to secure the strands to the mandrel. The heater/die is then closed and allowed to heat to temperature which takes approximately one hour.

2. Operating Cycle

The pultrusion machine is set up to run for the 14 days of daylight and then to be shut down for the 14 days of darkness. Before the start up, the creel is totally replenished with new packages of glass fiber and matrix to last for the 14 operating days. The machine automatically shuts down when the creel is empty.

V. COMPOSITE ROD

A. Glass Fibers

The glass used for the composite rods will be produced using the process designed by researchers at Clemson University. In short, the lunar surface (containing an abundance of silicon dioxide) will be used as the source of the glass. Since the production will be in the vacuum of space, the glass will be of a quality not attainable here on Earth. It is not clear the extent that this vacuum will increase the mechanical properties of the glass, so in calculating the properties of the resulting composites, the properties of S-glass were substituted. Since this is the best glass, mechanically, produced on Earth, it will serve as a good, conservative substitute for lunar glass in our calculations. The relevant properties of S-glass are listed in Table V. A. 1.

Table V. A. 1 - Properties of S-Glass

Density(g/cc)	2.5
Tensile Strength(ksi)	660
Tensile Modulus(Msi)	12.5
Compressive Modulus(Msi)	6.94
Coef. of Thermal Expansion(in/in/^{0}F)	3.0

The exact method of producing lunar glass has not yet been designed, but several assumptions were made about the process to complete this design. First, it was assumed that the glass could be produced in tow form, with linear density, and package size to our specification. In addition, all continuous glass fibers must have a size applied, and it was assumed that the glass would be supplied to the rod-producing machine with the size/coupling agent of our choice.

B. Matrix

The selection of the matrix for this process and composite was extremely complex. The extreme environment of the lunar surface made processing and end-use characteristics of the resin chosen very important. Many options for this role were considered - metals, ceramics, and polymers (both thermoplastics and thermosets). The metals were eliminated first, due to their extreme coefficients of thermal expansion and their high processing temperatures. Ceramics were also eliminated because of a susceptibility to brittle failure and complex processing procedures. The resulting group of possible matrices included both thermoplastic and thermoset polymers, but these were also not without problems.

The primary faults of normal polymer matrices when considered for this application are their susceptibility to radiation and their low glass transition and melting temperatures. Even if the temperature problems were solved, most polymer matrices would still require a radiation protective coating. In addition, thermoset resins usually require a solvent to impregnate the fibers with them, which would create another problem with flashing in the vacuum of the lunar environment. With all these considerations in mind, a potential list of thermoplastic resins was researched and the comparative properties are listed in Table V. B. 1.

Table V. B. 1. - Properties of Thermoplastic Resins

Property	Ultem 6000 (PEI)	Ultem 1000 (PEI)	Torlon 4203 (PAI)	Victrex (PEEK)	Xydar SRT-300 (LCP)	Vectra (LCP)
Melt Temp (^{0}F)	435	420	528	633	680	536
Tens. Stgth (psi)	15k	15.2k	27.8k	15k	20k	10.9k
Defl. Temp (^{0}F at 264 psi)	420	392	500	320	671	446

Additional comparative research on the above potential matrices determined that all except the liquid crystalline polymers (LCP's) would require a radiation coating to withstand the high level of radiation found on the lunar surface. This then narrowed our choices to Xydar and Vectra.

While Xydar is stronger, Vectra has a lower processing temperature making the energy requirements for processing lower. The primary benefit of Vectra, though, is that it is also produced in fibrous form under the name Vectran. This form would allow the pultrusion to be done with both the reinforcement fiber and matrix entering the heat die in fiberous form. This type process has not yet been attempted, but it would eliminate any potential problems with prepregging in the lunar environment.

Other than the experimental nature of fibrous matrix pultrusion, there are no other significant problems with the use of Vectran. The fiber's manufacturer, Hoechst Celanese, has already performed mechanical tests on Vectra as a matrix for glass coated with various coupling agents. These results have shown that fiber failure occurs in shear before matix failure, indicating that existing coupling agents would be a sufficient size for the lunar glass.

C. Composite Properties

The actual end uses of the pultruded rods were quite vague, so in determining the rod properties spreadsheets were set up to allow the designer to vary volume fraction, inner diameter, outer diameter, and length of the rods and to be able to calculate the critical tensile and compressive loads of the chosen rod.

1. Tension Analysis

In the analysis of the composite for tensional properties, constant stress across the area of the composite was assumed. By using the rule of mixtures for composite stress and substituting the fiber and matrix ultimate stresses, a simple formula for maximum tensile load can be found.

$$\sigma_c = \sigma_f V_f + \sigma_m V_m$$

$$\frac{P}{A_c} = \sigma_f V_f + \sigma_m (1 - V_f)$$

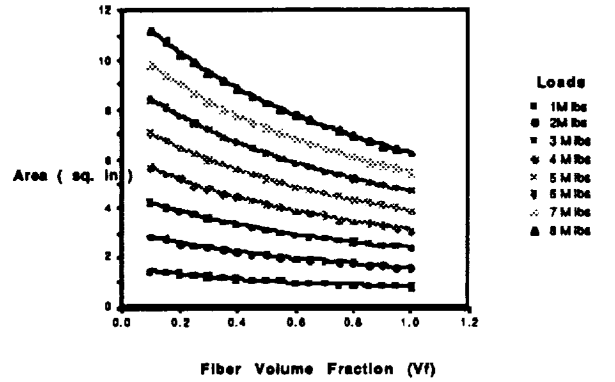
$$P_{max} = [(\sigma_{fu} - \sigma_{mu}) V_f + \sigma_{mu}] A_c$$

s_c = composite tensile stress
s_f = fiber tensile stress
s_m = matrix tensile stress
s_{fu} = fiber ultimate tensile stress
s_{mu} = matrix ultimate tensile stress
P = load
A_c = composite area
V_f = fiber volume fraction
V_m = matrix volume fraction

From this final formula, it is then possible to create a graph for composite area versus fiber volume fraction for given loads as in figure V. C. 1.

Figure V. C. 1:

Area vs Fiber Volume Fraction for Tensile Loads



2. Compression Analysis

In the analysis of the compression properties of the rods, 1st mode buckling was assumed to be the limiting factor for critical load. It is possible that the composite would fail due to microbuckling, but macrobuckling is far more likely in this composite's case. There are no standard equations to account for microbuckling, so the results of our compression analysis excludes it. By applying the standard buckling equation and applying the rule of mixtures for the composite modulus, a simple formula for critical compressive load was determined.

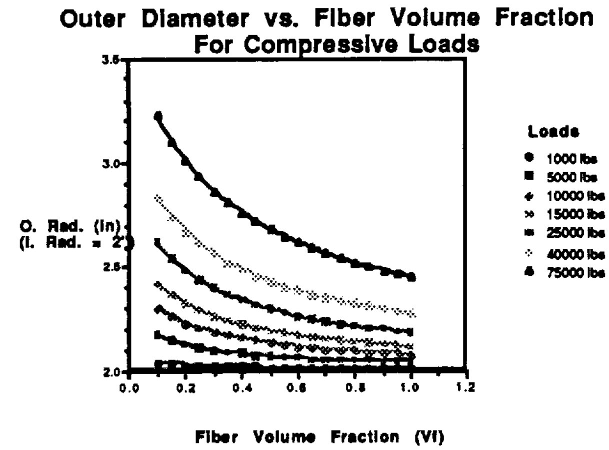
$$P_{cr} = n\frac{\pi^2 EI}{L^2}$$

$$P_{cr} = n\frac{\pi^3 (E_f V_f + E_m (1 - V_f))(R_o^4 - R_i^4)}{4L^2}$$

P_{cr} = critical compressive load
E_f = fiber compressive modulus
n = buckling mode
E_m = matrix compressive modulus
E = modulus
V_f = fiber volume fraction
I = moment of inertia
V_m = matrix volume fraction
L = rod length
R_o = outer radius
R_i = inner radius

By solving for R_o and setting n = 1, it is now possible to create a graph of outer radius versus volume fraction for given loads. This has been done in figure V. C. 2 for our composite rod of length = 10ft and inner radius = 2in (5cm).

Figure V.C.2:



From both the compression and tensile analysis, it is obvious that as the fiber content increases, theoretically, the compressive and tensile abilities of the composite increases. Also, as the fiber content increases, the amount of materials to be transported to the moon decreases as less matrix is required. It is quite clear, then that the maximum fiber content would be desirable for this design, but the maximum amount is limited by several factors.

As the fiber content increases beyond a point, there is not enough matrix to wet-out all of the fibers, so some are left unbonded. These free fibers weaken the structure, so that strengths actually decrease with a very high fiber volume fraction. Conventional pultrusion methods have produced fiber volume fractions as high as 70%, but because the matrix for this design will enter the die in fiber form, a conservative estimate would be that 60% fiber volume fraction would be the optimum amount. Based on this assumption, the 3m rod of inner diameter = 10cm and outer diameter = 12 cm would have the capacity to carry approximately 5 Msi in tension and 35 ksi in compression.

VI. COST ANALYSIS

The primary reason for undertaking this design project was to design a process for making glass fiber reinforced rods on the moon, for a weight and subsequent cost savings on the flights to the moon. Upon the completion of this design, it is now possible to perform a limited cost analysis of the project.

Based on the calculations for the 3 m rods with a 10 cm inner diameter and 12 cm outer diameter, one can calculate the relative weight savings:

Mass of Glass/14 Day Cycle: 11,756.5 kg
Mass of Machine + Matrix for one 14 day cycle: 7,957.4 kg (see appendix A)

Mass Savings after one 14 Day Cycle:
11,756.5 - 7957.4 = 3,799.1 kg

This calculation shows that to take up rods identical to those that could be made on the moon would require a cargo 3799.1 kg larger than that of the materials necessary to make the rods on the lunar surface. Based on the figure of \$100,000/lb of cargo, this translates to a savings of \$835.8M.

One of the major costs of using this design would be the required set-up and operating time required of an astronaut. These man hours include the initial set-up and the beginning of cycle set-up. The beginning of cycle set-up is estimated at five man-hours. At \$100,000/hr this would cost \$500,000. An estimation of the initial set-up is beyond our ability at this time, but with a surplus of cost savings of \$835.3M or 8355 man-hours, it seems obvious that even with a lengthy initial start-up, this design is easily justifiable for one cycle, and the savings will only increase as more rods are produced.

VII. CONCLUSIONS AND RECOMMENDATIONS

After studying the various types of composite manufacturing, it was concluded the pultrusion would be the most suitable method because of its simplicity and flexibility. Using the pultrusion method, hollow composite rods of 60% volume fraction glass fiber with a Vectra matrix, pultruded in fiber form, can be produced.

Though pultruding Vectra in fiber form would significantly simplify the problem of matrix application, it has never been done. It is believed, however, that the use of a fiber matrix is possible. Further research by Hoechst Celanese Corporation may prove this assumption.

In the cost analysis provided, it is clear that producing rods on the moon would provide significant savings over transporting rods manufactured on Earth to the moon. However, it is unclear if it would be cost efficient to produce rods of varying diameters. It has not been determined if the cost savings of matrix material and power consumption outweighs the cost of transporting different size dies and mandrels to the moon in order to produce varying sizes of rods.

It may be more cost efficient to produce a single size rod which will meet the needs of all rod applications. A further study of production and transportation costs would be necessary in order to determine the optimum size or sizes of rods to be produced.

In conclusion, the following recommendations are submitted for consideration:

1. A model pultrusion unit should be constructed and tested using Vectra fiber as a matrix to test for feasibility.

2. Further cost analysis should be conducted to determine the cost efficiency of varying rod diameters.

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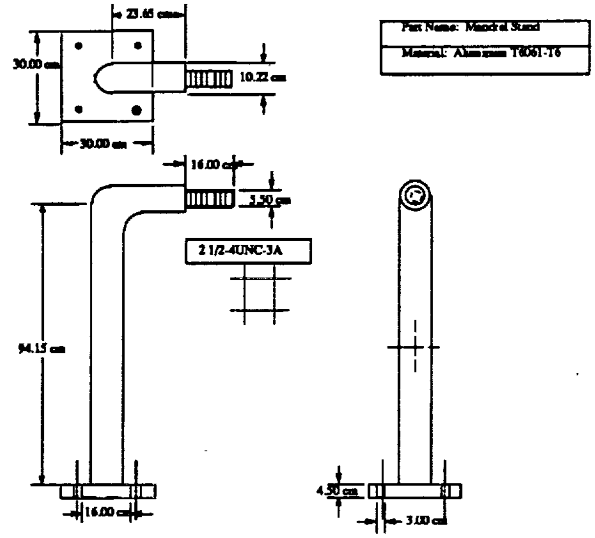
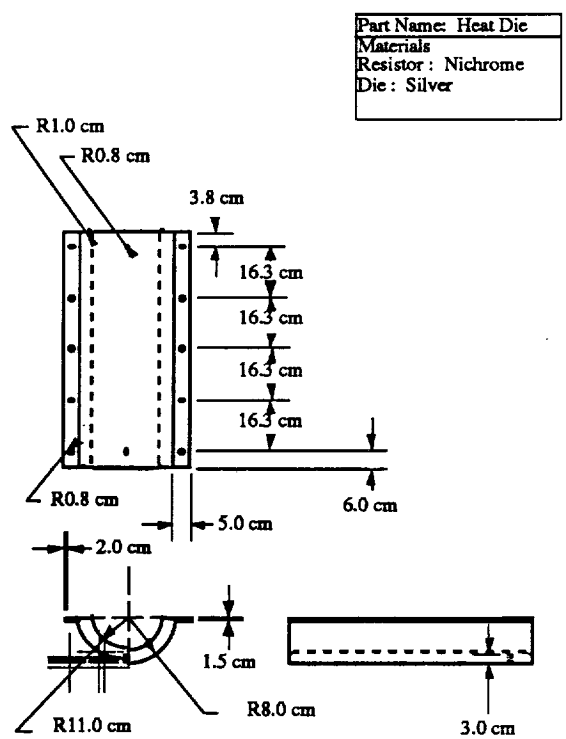
IX. APPENDICES

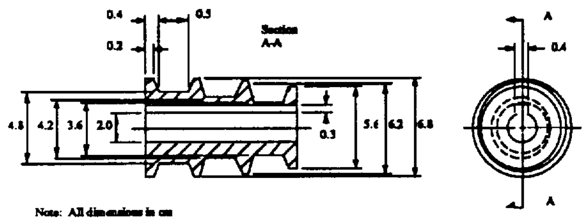
Appendix A

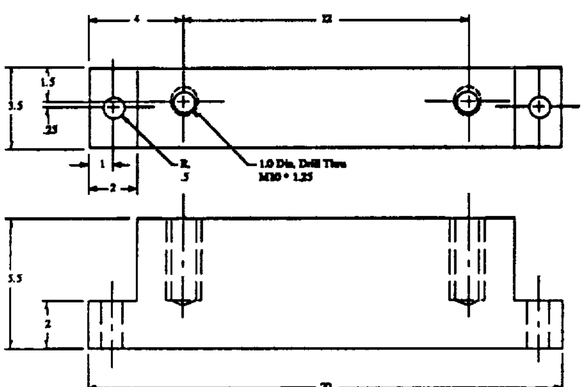
- Appendix A.1: MANDREL STAND
- Appendix A.2: HEAT DIE
- Appendix A.3: PULLEY
- Appendix A.4: BRACKET
- Appendix A.5: PULLER
- Appendix A.6: SCRAY
- Appendix A.7: RAILS
- Appendix A.8: THREADER
- Appendix A.9: MANDREL RUNNER





Pultrusion Pulley
Material: Al 6061 T6





Puller Bracket
Material: Al 6061-T6

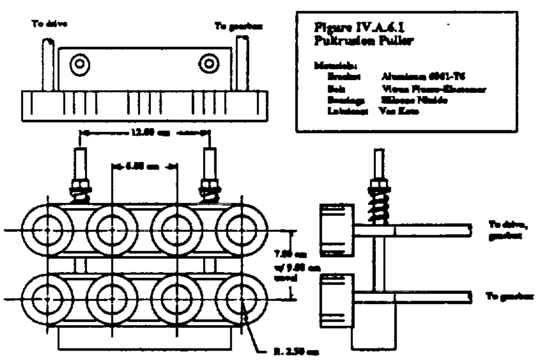
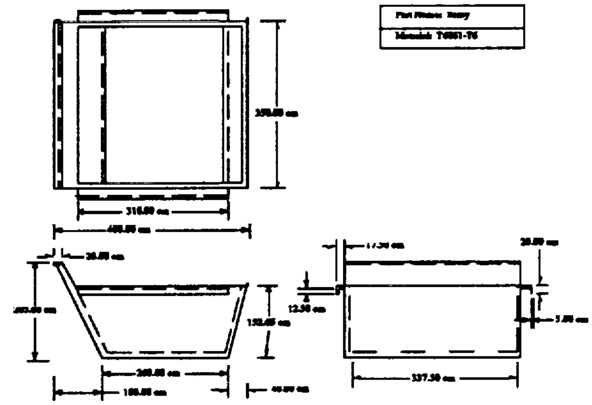
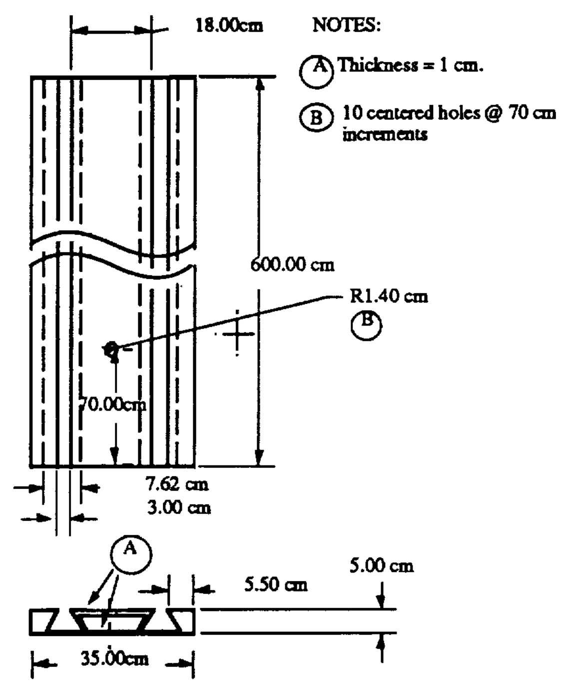
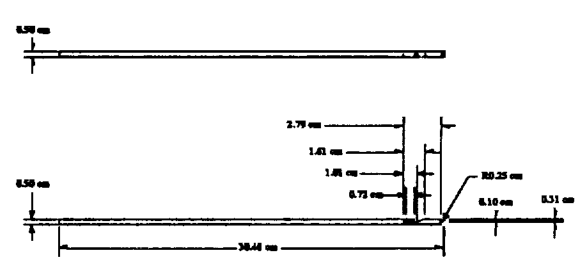


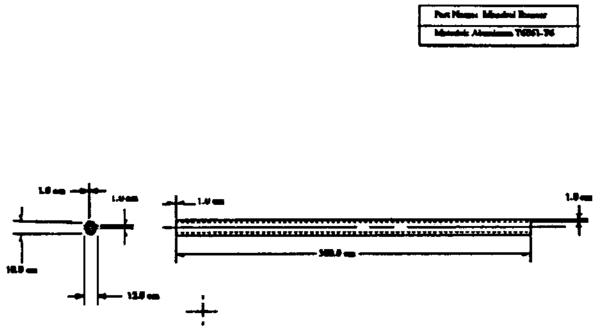
Figure IV.A.6.1
Pultrusion Puller

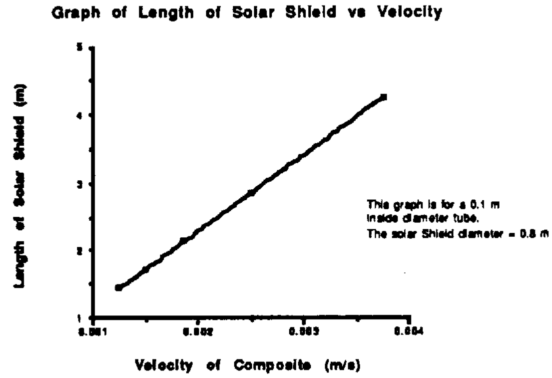


Part Name: Rails
Material: AL 6061-T6









Appendix B

Appendix C.1: GRAPH OF POWER VS LENGTH OF DIE

Appenidix C.2: GRAPH OF POWER VS VELOCITY

Appendix C.3: GRAPH OF LENGTH OF SHIELD VS VELOCITY